

Cryptographic method and apparatus for non-linearly merging a data block and a key

The invention relates to a method for converting a digital input block into a digital output block; said conversion comprising the step of merging a selected part M1 of said digital input block with a first key K1 and producing a data block B1 which non-linearly depends on said selected part M1 and said first key K1, and where a selected part of said digital output block is derived from said data block B1.

The invention further relates to an apparatus for cryptographically converting a digital input block into a digital output block; said apparatus comprising first input means for obtaining said digital input block; second input means for obtaining a first key K1; cryptographic processing means for converting the digital input block into the digital output block; said conversion comprising merging a selected part M1 of said digital input block with said first key K1 and producing a data block B1 which non-linearly depends on said selected part M1 and said first key K1, and where a selected part of said digital output block is derived from said data block B1; and output means for outputting said digital output block.

The Data Encryption Standard (DES) of the National Bureau of Standard [FIPS publication 46, 1977 January 15] describes a widely used algorithm for converting a digital input block into a digital output block. Such an algorithm is generally referred to as a block cipher. The DES algorithm is used for encrypting (enciphering) and decrypting (deciphering) binary coded information. Encrypting converts intelligible data, referred to as plaintext, into an unintelligible form, referred to as ciphertext. Decrypting the ciphertext converts the data back to its original form. In the so-called electronic code book mode, DES is used to encrypt blocks of 64 bits of plaintext into corresponding blocks of 64 bits of ciphertext. In this mode, the encryption uses keys which are derived from a 64 bit key, of which 56 bits may be freely selected. Figure 1 shows the overall structure of DES during encrypting. In the encrypting computation, the input (64 bit plaintext) is first permuted from 64 bits into 64 bits using a fixed permutation IP. The result is split into 32 left bits L_0 and 32 right bits R_0 . The right bits are transformed using a cipher function $f(R_0, K_1)$, where K_1 is a sub-key. The result $f(R_0, K_1)$ is added (bit-wise modulo 2) to the left bits, followed by interchanging the two resulting 32 bit blocks $L_0 \oplus f(R_0, K_1)$ and R_0 . This procedure is

continued iteratively for a total of 16 rounds. At the end of the last round the inverse permutation of the initial permutation IP is applied.

In the calculation of $f(R_i, K_{i+1})$ the 32 right bits R_i are first expanded to 48 bits in the box E, as illustrated in figure 2. According to a given table this expansion is performed by taking some input bits twice as an output bit and others only once. Then, the expanded 48 bits are added (bit-wise modulo 2) to the 48 key bits K_i . The resulting 48 bits are split into 8 groups of 6 bits each. Each of these groups is processed by an S box (S_i), which reduces the 6 bits to 4 bits in a non-linear operation. The eight S_i boxes are given in the form of a table. The total output is 32 bits, which is permuted in the box P. P is also given in the form of a table.

Figure 3 illustrates the key schedule calculation. The key consists of 64 bits, of which only 56 are used in the algorithm. Those 56 bits should be chosen randomly. Eight complementing error detecting bits are used to make the parity of each byte of the key odd. The selection of the 56 bits is performed in box PC1, together with a permutation. The result is split into two 28 bit words C_0 and D_0 . To obtain the 48 key bits for each round, first the words C_0 and D_0 are left shifted once or twice. A selection and a permutation PC2 are then applied to the result. The output of PC2 is the 48 bit sub-key K_1 which is used in $f(R_0, K_1)$. The process of shifting, selecting and permutating is repeated to generate a sub-key for each round. A table specifies how many shifts must be performed to obtain the next 48 bits of the sub-key for the following round.

The same algorithm and key can be used for decrypting a ciphertext. The initial permutation for the decrypting cancels the inverse permutation of the encrypting. Each round consists of a, so-called, Feistel cipher. It is well-known that for Feistel-ciphers the inverse operation consists of using the same rounds as used for encrypting but applying the sub-keys in inverse order. As such, the first decrypting round must be supplied with the same sub-key as used for the sixteenth encrypting round, the second decrypting round must be supplied with the same sub-key as used for the fifteenth encrypting round, etc. It is also well-known how the DES algorithm can be used in other encryption modes, such as the cipher feedback mode. In this mode, the DES algorithm is used to generate a stream of statistically random binary bits, which are combined with the plaintext, using, for instance, an exclusive-or logic operation.

The DES algorithm, in essence, comprises an initial permutation, followed by sixteen key-dependent computations on part of the data and terminated with an inverse permutation. Each key dependent computation comprises adding (modulo 2) key-

- dependent bits to the data part, followed by a non-linear operation on sub-blocks of the data part, and terminated by a permutation (linear operation) of the data part.

In general, DES is considered to be a good encryption/decryption tool. It is, however, an open question whether or not DES has remained secure over the past years, particularly in view of the recent very powerful differential cryptanalytic attacks.

It is an object of the invention to provide a cryptographic method and apparatus of the kind set forth which is more robust against cryptanalytic attacks.

To achieve this object, the cryptographic method according to the invention is characterised in that said merging step is performed by executing a non-linear function g for non-linearly merging said selected part $M1$ and said first key $K1$ in one, sequentially inseparable step. In the DES system, as shown in figure 2, in a first processing step the R data is bit-wise added to the key, followed by a second processing step of non-linearly processing the result (S-boxes). According to the invention, an algorithm is used which non-linearly merges data with a key in one step (i.e. one, sequentially inseparable step). As such, adding the key bits to the data is an integrated part of the non-linear operation, making the system more immune against modern attacks, such as differential cryptanalysis.

In an embodiment of the method according to the invention as defined in the dependent claim 2, in each round both parts of the digital input block are processed, giving a better encryption result than for conventional Feistel ciphers, such as DES, where during each round only half of the digital input block is being processed. To ensure that the same system can be used for both encryption and decryption, one part of the data is processed using an operation g , whereas the other half is processed using the inverse operation g^{-1} . Using this scheme, decrypting is performed by using the same system but supplying the keys in reverse order to the rounds (during decryption the first non-linear step is supplied with the key which, during encryption, was supplied to the last non-linear step, etc.). Compared to a conventional implementation of a Feistel cipher with twice as many rounds, the system according to the invention is faster.

The measure as defined in the dependent claim 3, wherein a relatively large data block and key, of for instance 64 bits, are split into smaller sub-blocks and sub-keys simplifies real-time non-linear processing.

In an embodiment of the method according to the invention as defined in the dependent claim 5, a constant is used to enhance the quality of the encryption. Advan-

tageously, the constant is predetermined per system, forming, for instance, a customer-specific constant. Alternatively, the constant is generated using a pseudo-random generator.

The measure defined in dependent claim 6 provides a way for non-linearly merging the data sub-block and the sub-key in one step. Additionally, different inputs all
5 result in different outputs. This increases the immunity of the system against cryptanalytic attacks, compared to DES where the non-linear operation reduces the 6-bit input sub-block to a 4-bit output sub-block, implying that the same output is produced for four different inputs.

In an embodiment of the method according to the invention as defined in the dependent claim 7 a constant is used to enhance the quality of the encryption. Advan-
10 tageously, the constant is predetermined per system, forming, for instance, a customer-specific constant. Alternatively, the constant is generated using a pseudo-random generator.

The measure as defined in the dependent claim 8 increases the quality of the encryption even further.

In an embodiment of the method according to the invention as defined in the dependent claim 10 individual sub-blocks corresponding to different parts of the digital
15 input block are swapped to improve the quality of the encryption.

Preferably, the sub-block m_i comprises eight data bits. This further improves the quality of the non-linear operation compared to DES, where the non-linear operation converts six to four bits.

The measure as defined in the dependent claim 11 has the advantage of reducing the multiplication in $GF(2^8)$ to operations in $GF(2^4)$, making it possible to achieve a
20 simpler or more cost-effective implementation.

The measure defined in the dependent claim 12 gives an effective way of reducing the multiplication in $GF(2^8)$ to operations in $GF(2^4)$.

25 An embodiment of the method according to the invention is characterised in that β is a root of an irreducible polynomial $h(x) = x^4 + x^3 + x^2 + x + 1$ over $GF(2)$. This is a preferred choice for β , allowing the use of the so-called shifted polynomial base.

An embodiment of the method according to the invention is characterised in that calculating the inverse of an element of $GF(2^8)$ comprises performing a series of
30 calculations in $GF(2^4)$. By reducing the inverse operation in $GF(2^8)$ to operations in $GF(2^4)$ a simpler or more-cost effective implementation can be achieved.

An embodiment of the method according to the invention is characterised in that calculating the inverse of said element b comprises calculating
 $(a_0^2 + a_0 a_1 + a_1^2 \beta)^{-1}((a_0 + a_1) + a_1 D)$. This is an effective way of reducing the inverse operation

in $GF(2^8)$ to operations in $GF(2^4)$.

An embodiment of the method according to the invention is characterised in that said first key K1 comprises 64 data bits and wherein each of said sub-keys k_i comprises eight data bits. By using a large key the quality of the encryption is increased.

5 To achieve the object of the invention, the apparatus according to the invention is characterised in that said cryptographic processing means is arranged to perform said merging by executing a non-linear function g for non-linearly merging said selected part M1 and said first key K1 in one, sequentially inseparable step.

10 These and other aspects of the invention will be apparent from and elucidated with reference to the embodiments shown in the drawings.

Figure 1 shows the processing steps for the DES system,

15 Figure 2 illustrates details of merging the data with the key and the non-linear operation in DES,

Figure 3 illustrates details of the key calculation in DES,

Figure 4 shows a block diagram of the cryptographic apparatus,

20 Figure 5 illustrates separate processing of two parts of the digital input block,

Figure 6 illustrates processing of a part of the digital input block in the form of sub-blocks,

Figure 7 illustrates processing of two parts in the form of sub-blocks, and

Figure 8 shows an overall encryption system.

25 Figure 4 shows a block diagram of the cryptographic apparatus 400 according to the invention. For the purpose of explaining the invention, the system is described in the electronic code book mode. Persons skilled in the art will be able to use the system in other modes as well. The apparatus 400 comprises first input means 410 for obtaining a digital input block M. The digital input block M may be any suitable size.

30 Preferably, M is sufficiently large, for instance 128 bits, to obtain a reasonably secure encryption result. The apparatus 400 further comprises cryptographic processing means 420 for converting the digital input block into a digital output block. Advantageously, the digital output block has substantially equal length as the digital input block. The apparatus 400 comprises output means 430 for outputting the digital output block. Basically, the

cryptographic processing means 420 converts the digital input block M into the digital output block by merging a selected part M1 of the digital input block M with a first key K1, producing a data block B1 which non-linearly depends on M1 and K1. The merging is performed in one, sequentially inseparable step. The digital output block is derived from B1 and the remaining part of M, which is not part of M1. To obtain the first key K1, the cryptographic apparatus 400 comprises second input means 440. As will be described in more details below, a second part M2 of the digital input block may be non-linearly merged with a second key K2, preferably, using an operation inverse to the operation for merging M1 and K1, producing a data block B2. In this case, the digital output block also depends on B2. To obtain the second key K2, the cryptographic apparatus 400 comprises third input means 450.

It will be appreciated that the cryptographic apparatus 400 may be implemented using a conventional computer, such as a PC, or using a dedicated encryption/decryption device. The digital input block may be obtained in various ways, such as via a communication network, from a data storage medium, such as a harddisk or floppy disk, or directly being entered by a user. Similarly, the digital output block may be output in various ways, such as via a communication network, stored on a data storage medium, or displayed to a user. Preferably, secure means are used to this end. The cryptographic processing means 420 may be a conventional processor, such as for instance used in personal computers, but may also be a dedicated cryptographic processor. The cryptographic apparatus 400 may, in part or in whole, be implemented on a smart-card.

In the remainder of the document details of the cryptographic conversion are given for encrypting blocks of 128 bits of plaintext into corresponding blocks of 128 bits of ciphertext. Persons skilled in the art will be able to use the system for other block sizes as well. Data sizes shown in the Figures are given for reasons of clarity and should be treated as examples only. The description focuses on the non-linear processing of the data and the merging of the key with the data as performed in one round. As such the invention can be applied in a system as shown in Figure 1, comprising multiple rounds and also including a linear operation on the data block in each round.

As shown in Figure 5, the message block M of 128 bits is divided into a first part M1 and a second part M2 (a left and a right block). Preferably, both parts are of equal size, 64 bits. It will be appreciated that M1 and M2 may also be derived from M using a more complicated selection process. M1 is processed using a non-linear function g. In principle, it is not required to process M2 during the same round. Advantageously, M2 is

processed in the same round using the inverse function g^{-1} . Each of the functions g and g^{-1} non-linearly merges, M1 or, respectively, M2 with a key K1 or, respectively K2. Preferably, the data parts and the keys have the same size. Since it is difficult to implement a good non-linear operation on a large data block and non-linearly processing a large data block is time consuming, the data parts M1 and M2 are split into sub-blocks. Figure 6 illustrates this for M1. Figure 7 illustrates the splitting of M1 and M2. Using 64-bit data parts M1 and M2, advantageously, the parts are each split into eight 8-bit elements, where $M1 = (m_0, m_1, \dots, m_7)$ and $M2 = (m_8, m_9, \dots, m_{15})$. The two keys K1 and K2 may be derived from a larger key, for instance, by splitting a 128 bit key into two 64-bit keys K1 and K2. The two keys K1 and K2 may be split further. Using 64-bit keys, advantageously, each key is split into 8-bit sub-keys, giving a total of sixteen 8-bit sub-keys k_j , $j = 0..15$. Each of the sub-keys k_j is associated with the corresponding sub-block m_j . Each sub-block is processed separately. Preferably, the sub-blocks are processed in parallel. If preferred, the sub-blocks relating to one round may also be serially processed. The first group of sub-blocks, forming M1, are each processed by a cipher function f . The second group of sub-blocks are each processed by the inverse function f^{-1} .

For the cryptographic operations, an n -bit sub-block or sub-key is considered to represent an element of $GF(2^n)$ (Galois Field). All operations are, therefore, in $GF(2^n)$.

In its basic form, the cipher function f has two inputs m_j and k_j and one output t_j as also illustrated in figures 6 and 7, where $t_j = f(m_j, k_j)$, for $j = 0$ to 7. In the basic form, the cipher function f involves one operation $h(b_j, k_j)$ with an output of substantially equal size as b_j . The function h has a data sub-block b_j and a sub-key k_j as input, where $b_j = m_j$ for the basic form of the cipher function f . The function f (in this embodiment the same as the function h) is defined as follows for $j = 0..7$:

$$1. \quad h(b_j, k_j) = \begin{cases} (b_j \cdot k_j)^{-1}, & \text{if } b_j \neq 0, k_j \neq 0, \text{ and } b_j \neq k_j \\ (k_j)^{-2}, & \text{if } b_j = 0 \\ (b_j)^{-2}, & \text{if } k_j = 0 \\ 0, & \text{if } b_j = k_j \end{cases}$$

Similarly, in its basic form the inverse cipher function f^{-1} has two inputs m_j and k_j and one output t_j as also illustrated in figures 6 and 7, where $t_j = f^{-1}(m_j, k_j)$, for $j = 8$ to 15. The inverse cipher function f^{-1} involves also one operation, $h^{-1}(b_j \cdot k_j)$ with an output of substantially equal size as b_j . The function h^{-1} is the inverse of h . As before, $b_j = m_j$ in the basic form of the cipher function f^{-1} . The function f^{-1} (in this embodiment the same

as the functions h^{-1} is defined as follows for $j = 8..15$:

$$\begin{aligned}
 1. \quad h^{-1}(b_j \cdot k_j) = & \begin{aligned} & (b_j \cdot k_j)^{-1}, & \text{if } b_j \neq 0, k_j \neq 0, \text{ and } b_j \cdot k_j^2 \neq 1 \\ & k_j, & \text{if } b_j = 0 \\ & (b_j)^{-1/2}, & \text{if } k_j = 0 \\ & 0, & \text{if } b_j \cdot k_j^2 = 1 \end{aligned}
 \end{aligned}$$

In a further embodiment, the outputs t_j of the cipher functions f ($t_j = f(m_j, k_j)$, for $j = 0$ to 7) and the outputs of the inverse cipher function f^{-1} ($t_j = f^{-1}(m_j, k_j)$, for $j = 8$ to 15) are swapped in the following manner: $t_j \leftrightarrow t_{15-j}$ for $j = 0$ to 7 . This is illustrated in Figure 7.

In a further embodiment, a constant is added (bit-wise module 2) to each data sub-block m_j before executing the function h . Preferably, eight independent constants p_j ($j = 0..7$) are used, each being added to the corresponding data sub-block m_j . The same function h is used as before, now operating on $b_j = m_j \oplus p_j$. The cipher function f is now defined as follows:

$$\begin{aligned}
 1. \quad b_j &= m_j \oplus p_j \\
 2. \quad h(b_j, k_j) &= \begin{aligned} & (b_j \cdot k_j)^{-1}, & \text{if } b_j \neq 0, k_j \neq 0, \text{ and } b_j \neq k_j \\ & (k_j)^{-2}, & \text{if } b_j = 0 \\ & (b_j)^{-2}, & \text{if } k_j = 0 \\ & 0, & \text{if } b_j = k_j \end{aligned}
 \end{aligned}$$

Similarly, for the inverse cipher function f^{-1} also a constant is added (bit-wise module 2) to each data sub-block m_j . To allow the inverse function f^{-1} to be used to decrypt text encrypted using the cipher function f , the constant is added after the function h . Preferably, the same eight independent constants p_j ($j = 0..7$) are used as used for the cipher function f . Now, the constants p_j are being added to the $15-j$ -th stream

($j = 0..7$). As a consequence, the inverse cipher function f^{-1} involves the following two operations ($j = 8..15$):

$$\begin{aligned}
 1. \quad h^{-1}(b_j \cdot k_j) &= \begin{aligned} & (b_j \cdot k_j)^{-1}, & \text{if } b_j \neq 0, k_j \neq 0, \text{ and } b_j \cdot k_j^2 \neq 1 \\ & k_j, & \text{if } b_j = 0 \\ & (b_j)^{-1/2}, & \text{if } k_j = 0 \\ & 0, & \text{if } b_j \cdot k_j^2 = 1 \end{aligned}
 \end{aligned}$$

$$2. \quad t_j = h^{-1}(b_j \cdot k_j) \oplus p_{15-j}$$

Finally, t_j and t_{15-j} are swapped ($j = 0..7$).

In a further embodiment, a further constant is added (bit-wise module 2) to each data sub-block m_j after executing the function h . Preferably, eight independent

constants d_j ($j = 0..7$) are used, each being added to the corresponding data sub-block m_j .

The same function h is used as before. The cipher function f is now defined as follows:

1. $b_j = m_j \oplus p_j$
2. $h(b_j, k_j) = \begin{cases} (b_j \cdot k_j)^{-1}, & \text{if } b_j \neq 0, k_j \neq 0, \text{ and } b_j \neq k_j \\ (k_j)^{-2}, & \text{if } b_j = 0 \\ (b_j)^{-2}, & \text{if } k_j = 0 \\ 0, & \text{if } b_j = k_j \end{cases}$
3. $t_j = h(b_j, k_j) \oplus d_j$

Similarly, for the inverse cipher function f^{-1} also a constant is added (bit-wise module 2) to each data sub-block m_j . To allow the inverse function f^{-1} to be used to decrypt text encrypted using the cipher function f , the constant is added before executing the function h . Preferably, the same eight independent constants d_j ($j = 0..7$) are used as used for the cipher function f . Now, the constants d_j are being added to the 15-j-th stream ($j = 0..7$). The same function h^{-1} is used as before, now operating on $b_j = m_j \oplus d_{15-j}$. As a consequence, the inverse cipher function f^{-1} involves the following three operations ($j = 8..15$):

1. $b_j = m_j \oplus d_{15-j}$
2. $h^{-1}(b_j \cdot k_j) = \begin{cases} (b_j \cdot k_j)^{-1}, & \text{if } b_j \neq 0, k_j \neq 0, \text{ and } b_j \cdot k_j^2 \neq 1 \\ k_j, & \text{if } b_j = 0 \\ (b_j)^{-1/2}, & \text{if } k_j = 0 \\ 0, & \text{if } b_j \cdot k_j^2 = 1 \end{cases}$
3. $t_j = h^{-1}(b_j \cdot k_j) \oplus p_{15-j}$

Finally, t_j and t_{15-j} are swapped ($j = 0..7$).

It will be appreciated that it is also possible to use the constants d_j without using constants p_j .

In a further embodiment, the cipher function f raises the outcome of the function h to a power of two. The same function h is used as before. The cipher function f is now defined as follows:

1. $b_j = m_j \oplus p_j$
2. $h(b_j, k_j) = \begin{cases} (b_j \cdot k_j)^{-1}, & \text{if } b_j \neq 0, k_j \neq 0, \text{ and } b_j \neq k_j \\ (k_j)^{-2}, & \text{if } b_j = 0 \\ (b_j)^{-2}, & \text{if } k_j = 0 \\ 0, & \text{if } b_j = k_j \end{cases}$
3. $s_j = h(b_j, k_j)^{2^{+i}}$
4. $t_j = s_j \oplus d_j$

Similarly, the inverse cipher function f^{-1} also raises a data sub-block to a power of 2. To

allow the inverse function f^{-1} to be used to decrypt text encrypted using the cipher function f , the additional operation is performed before executing the function h . The same function h^{-1} is used as before, now operating on $b_j = m_j \oplus d_{15-j}$. As a consequence, the inverse cipher function f^{-1} involves the following four operations ($j = 8..15$):

1. $q_j = m_j \oplus d_{15-j}$
2. $b_j = q_j^{2^{(j-7)}}$
2. $h^{-1}(b_j \cdot k_j) = \begin{cases} (b_j \cdot k_j)^{-1}, & \text{if } b_j \neq 0, k_j \neq 0, \text{ and } b_j \cdot k_j^2 \neq 1 \\ k_j, & \text{if } b_j = 0 \\ (b_j)^{-1/2}, & \text{if } k_j = 0 \\ 0, & \text{if } b_j \cdot k_j^2 = 1 \end{cases}$
3. $t_j = h^{-1}(b_j \cdot k_j) \oplus p_{15-j}$

Finally, t_j and t_{15-j} are swapped ($j = 0..7$).

It will be appreciated that it is also possible to use the operation of raising to a power of 2 without using one or both of the constants d_j and p_j .

For decrypting the same algorithm is used as for encrypting, but the sub-keys are swapped: instead of k_j , k_{15-j} is used, $j = 0 .. 15$.

The multiplication in $GF(2^8)$

In principle, for the invention any multiplication in $GF(2^8)$ may be used.

An example of a VLSI implementation of multiplications in $GF(2^m)$ is given in [P. A. Scott, "A fast VLSI multiplier for $GF(2^m)$ ", IEEE Journal on selected areas in communications, Vol. SAC-4, No. 1, January 1986, pages 62-66]. Advantageously, the following mechanism is used to reduce the multiplication in $GF(2^8)$ to a series of multiplications and additions in $GF(2^4)$.

Let in $GF(2^4)$, β be the non-trivial root of $\beta^5 = 1$ (non-trivial means $\beta \neq 1$, or, equally, β is the root of the irreducible polynomial $h(x) = x^4 + x^3 + x^2 + x + 1$ over $GF(2)$, since: $x^5 + 1 = (x + 1)(x^4 + x^3 + x^2 + x + 1)$). The normal base $\beta, \beta^2, \beta^4, \beta^8$ is taken as the base in $GF(2^4)$. Since according to the polynomial $\beta^8 = \beta^3$, this is the same as the so-called shifted polynomial base: $\beta, \beta^2, \beta^3, \beta^4$.

Let D be an element of $GF(2^8)$, defined as a root of the irreducible polynomial $k(x) = x^2 + x + \beta$ over $GF(2^4)$. Every element of $GF(2^8)$ can be represented as $a_0 + a_1.D$, with a_0 and a_1 being elements of $GF(2^4)$. In binary terminology, the number b of $GF(2^8)$ can be represented using eight bits, arranged as a vector (a_0, a_1) , with a_0, a_1 having four bits, representing numbers of $GF(2^4)$. As such, the base in $GF(2^8)$ is: $\beta, \beta^2, \beta^3, \beta^4, D\beta,$

$D\beta^2, D\beta^3, D\beta^4$. Two elements b and c of $GF(2^8)$, represented as $b = a_0 + a_1.D$ and $c = a_2 + a_3.D$, with $a_i \in GF(2^4)$, can be multiplied as follows:

$$b.c = (a_0 + a_1.D).(a_2 + a_3.D) = a_0a_2 + (a_1a_2 + a_0a_3).D + a_1a_3.D^2.$$

Using the fact that D is a root of $k(x)$, which implies that: $D^2 = D + \beta$, this gives the

5 multiplication result:

$$b.c = (a_0a_2 + a_1a_3\beta) + (a_1a_2 + a_0a_3 + a_1a_3).D.$$

This has reduced the multiplication of two elements of $GF(2^8)$ to a series of multiplications and additions in $GF(2^4)$.

10 The inverse in $GF(2^8)$

In principle any known method may be used to calculate the inverse of an element in $GF(2^8)$. Advantageously, if the previous method has been used to reduce the multiplication in $GF(2^8)$ to a multiplication in $GF(2^4)$, then the following method is used to reduce the inverse operation in $GF(2^8)$ to an inverse operation in $GF(2^4)$.

The inverse b^{-1} of an element b in $GF(2^8)$, where b is represented as $b = a_0 + a_1.D$, with $a_i \in GF(2^4)$, is given by:

$$b^{-1} = (a_0^2 + a_0a_1 + a_1^2\beta)^{-1} \cdot (a_0 + a_1 + a_1D), \text{ since:}$$

$$\begin{aligned} b^{-1}.b &= (a_0^2 + a_0a_1 + a_1^2\beta)^{-1} \cdot (a_0 + a_1 + a_1D) \cdot (a_0 + a_1D) \\ &= (a_0^2 + a_0a_1 + a_1^2\beta)^{-1} \cdot (a_0^2 + a_0a_1 + a_1^2D + a_1^2D^2), \end{aligned}$$

20 and since $D^2 + D = \beta$, this gives: $b^{-1}.b = 1$.

In this way the inverse operation in $GF(2^8)$ is reduced to an inverse operation in $GF(2^4)$ and a series of multiplications and additions in $GF(2^4)$.

Multiplication in $GF(2^4)$

25 In principle, any multiplication in $GF(2^4)$ may be used. Advantageously, as described before, the shifted polynomial base $\beta, \beta^2, \beta^3, \beta^4$ is taken as the base in $GF(2^4)$, where β is the root of the irreducible polynomial $h(x) = x^4 + x^3 + x^2 + x + 1$ over $GF(2)$, and $\beta^5 = 1$ in $GF(2^4)$. Since β is a root of h , this implies:

$$\beta^4 + \beta^3 + \beta^2 + \beta = 1. \text{ Assuming that the base elements are named } e_1, e_2, e_3 \text{ and } e_4, \text{ with } e_1$$

30 $= \beta^1$, the base elements are multiplied in the following way, using the definition of β :

$$e_1.e_1 = \beta.\beta = \beta^2 = e_2$$

$$e_1.e_2 = \beta.\beta^2 = \beta^3 = e_3$$

$$e_1.e_3 = \beta.\beta^3 = \beta^4 = e_4$$

$$e_1.e_4 = \beta.\beta^4 = \beta^5 = 1 = e_1 + e_2 + e_3 + e_4$$

$$e_2.e_2 = \beta^2.\beta^2 = \beta^4 = e_4$$

$$e_2.e_3 = \beta^2.\beta^3 = \beta^5 = 1 = e_1 + e_2 + e_3 + e_4$$

$$e_2.e_4 = \beta^2.\beta^4 = \beta^6 = \beta = e_1$$

$$e_3.e_3 = \beta^3.\beta^3 = \beta^6 = \beta = e_1$$

$$5 \quad e_3.e_4 = \beta^3.\beta^4 = \beta^7 = \beta^2 = e_2$$

$$e_4.e_4 = \beta^4.\beta^4 = \beta^8 = \beta^3 = e_3$$

This in principle defines the multiplication in $GF(2^4)$. In binary terms the multiplication can be seen as follows. With respect to the base, each element b in $GF(2^4)$ can be represented as $b = b_0e_1 + b_1e_2 + b_2e_3 + b_3e_4$, with $b_i \in GF(2)$. As such, the element b can be represented

10 by a 4-dimensional vector with binary components (b_0, b_1, b_2, b_3) . On a micro-processor this can be represented using a nibble. In binary terms, the multiplication of two elements b and c in $GF(2^4)$ can be seen as follows, assuming the two elements are represented by $b = (b_0, b_1, b_2, b_3)$ and $c = (c_0, c_1, c_2, c_3)$. Multiplying the two elements in the normal way gives:

$$15 \quad b.c = (b_0c_0)\beta^2 + (b_0c_1 + b_1c_0)\beta^3 + (b_0c_2 + b_1c_1 + b_2c_0)\beta^4 + \\ (b_0c_3 + b_1c_2 + b_2c_1 + b_3c_0)\beta^5 + (b_1c_3 + b_2c_2 + b_3c_1)\beta^6 + \\ (b_2c_3 + b_3c_2)\beta^7 + (b_3c_3)\beta^8$$

Using the definition of β to replace β^5 by $\beta^4 + \beta^3 + \beta^2 + \beta$, β^6 by β , β^7 by β^2 , and β^8 by β^3 , gives the following four components:

$$20 \quad b.c = (b_1c_3 + b_2c_2 + b_3c_1 + b_0c_3 + b_1c_2 + b_2c_1 + b_3c_0)\beta + (b_0c_0 + b_2c_3 + b_3c_2 + b_0c_3 + \\ b_1c_2 + b_2c_1 + b_3c_0)\beta^2 + (b_0c_1 + b_1c_0 + b_3c_3 + b_0c_3 + b_1c_2 + b_2c_1 + b_3c_0)\beta^3 + (b_0c_2 + b_1c_1 + \\ b_2c_0 + b_0c_3 + b_1c_2 + b_2c_1 + b_3c_0)\beta^4$$

The result of the multiplication, in binary terms, is, therefore, given by:

$$25 \quad b.c = (\quad b_1c_3 + b_2c_2 + b_3c_1 + b_0c_3 + b_1c_2 + b_2c_1 + b_3c_0, \\ b_0c_0 + b_2c_3 + b_3c_2 + b_0c_3 + b_1c_2 + b_2c_1 + b_3c_0, \\ b_0c_1 + b_1c_0 + b_3c_3 + b_0c_3 + b_1c_2 + b_2c_1 + b_3c_0, \\ b_0c_2 + b_1c_1 + b_2c_0 + b_0c_3 + b_1c_2 + b_2c_1 + b_3c_0)$$

Inverse operation in $GF(2^4)$

30 Using the normal base $\beta, \beta^2, \beta^4, \beta^8$, each element x of $GF(2^4)$ can be written as $b = a.\beta + b.\beta^2 + c.\beta^4 + d.\beta^8$, with $a, b, c, d \in GF(2)$. As such, each element can be represented by a 4-dimensional vector (a, b, c, d) .

In order to obtain the inverse of b (b^{-1}):

calculate the following intermediate results: $ab, a\bar{b}, \bar{a}b, bc, \bar{b}c, b\bar{c}, cd, \bar{c}d$,

$c\bar{d}$, da , $\bar{d}a$, $d\bar{a}$, where ab is the binary AND of a and b ($a \text{ AND } b$) and \bar{a} is the binary complement of a (NOT a).

- calculate the first bit of b^{-1} by using cd , $\bar{c}d$, $c\bar{d}$, $\bar{a}b$, $b\bar{c}$, and $\bar{d}a$ as follows:

$(cd) \text{ OR } (\bar{a} \text{ AND } c\bar{d}) \text{ OR } (\bar{c}d \text{ AND } \bar{a}b) \text{ OR } (b\bar{c} \text{ AND } \bar{d}a)$

5 - calculate the second bit of b^{-1} by using da , $\bar{d}a$, $d\bar{a}$, $\bar{b}c$, $c\bar{d}$, $\bar{a}b$ as follows:

$(da) \text{ OR } (\bar{b} \text{ AND } d\bar{a}) \text{ OR } (\bar{d}a \text{ AND } \bar{b}c) \text{ OR } (c\bar{d} \text{ AND } \bar{a}b)$

- calculate the third bit of b^{-1} by using ab , $\bar{a}b$, $a\bar{b}$, $\bar{c}d$, $d\bar{a}$, $\bar{b}c$ as follows:

$(ab) \text{ OR } (\bar{c} \text{ AND } a\bar{b}) \text{ OR } (\bar{a}b \text{ AND } \bar{c}d) \text{ OR } (d\bar{a} \text{ AND } \bar{b}c)$

- calculate the fourth bit of b^{-1} by using bc , $\bar{b}c$, $b\bar{c}$, $\bar{d}a$, $a\bar{b}$, $\bar{c}d$ as follows:

10 $(bc) \text{ OR } (\bar{d} \text{ AND } b\bar{c}) \text{ OR } (\bar{b}c \text{ AND } \bar{d}a) \text{ OR } (a\bar{b} \text{ AND } \bar{c}d)$

Besides being used in a DES-like system as shown in Figure 1, a dedicated system can be built around the non-linear algorithm of the invention. Such a system is shown in figure 8. In this system, the blocks are processed using the non-linear operation NL of the invention and a linear operation LIN. The first step is the non-linear operation. This is followed by an iteration of the linear operation followed by the non-linear operation. It is expected that a sufficiently safe system is achieved by performing six non-linear operations (i.e. using five rounds), provided that the linear operation mixes the data bits thoroughly. Preferably, 15 rounds are used. Each of the linear operations is the same. Also, each of the non-linear operations is the same, but each non-linear operation uses a different key of 128 bits. Advantageously, keys are derived from one global key of, for instance, 256 bits, using a key schedule calculation. The same key is used for encryption as well as decryption. In most cases the key is provided using a smart-card. For the linear operation, advantageously, instead of a permutation a more complex matrix is used. As described before, in addition to the key, each non-linear operation may, optionally, use a constant C of 128 bits, which is split in the constants p_j and d_j . The constant may be the same for each operation. Advantageously, each non-linear operations is provided with a separate constant. The constants may be predetermined per system (e.g. a customer-specific constant). Alternatively, the constant is generated using a pseudo-random generator.